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RELATIVE OPERATING CAPABILITIES OF SELECTED ELECTRIC-ARC REENTRY ENVIRONMENT SIMULATORS

by N. K. Hiester and C. F. Clark

Prepared under Contract No. NASr-49(15) *by*
STANFORD RESEARCH INSTITUTE
Menlo Park, Calif.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1964

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I INTRODUCTION

Stanford Research Institute has been engaged by National Aeronautics and Space Administration to determine the feasibility of developing meaningful standard evaluation procedures for testing ablating materials used in reentry-type thermal protection systems. This involves definition of the extent to which realistic environmental conditions are simulated by existing test devices, initiation of comparative tests on specific materials in several of these devices, and correlation and analysis of the results to determine the feasibility of developing a standardized test. A more detailed description of the program is contained in Quarterly Progress Report No. 1.

In order to undertake these comparative tests it is necessary to know the relative capabilities of the various test facilities. This report describes the procedure used to obtain and evaluate this information and presents the indicated operating envelopes for the organizations participating in the round-robin ablation program.

II SUMMARY

A technique is described for estimating the operating envelopes for supersonic electric arc air heaters. This involves utilization of a minimum amount of actual performance data plus determination of the upper and lower enthalpy, arc chamber pressure, and power input limits for the arc heater. The method of Winovich (NASA TN D-2132) is then used to predict the enthalpy-arc chamber pressure envelope. Knowledge of the normal shock pressure recovery ratio (estimated through NASA TN D-693) from the nozzle area ratio, plus use of the laminar stagnation-point heating rate formula obtained from the Fay-Riddell analysis, permit conversion of this envelope to an enthalpy-heating rate envelope.

Information of the above type was gathered from the participating organizations in the round-robin ablation program and used to predict the operating envelopes for these facilities. Actual envelopes were then requested and in general were found to compare well with those predicted.

This good agreement indicates that the prediction technique employed is valid and represents an important contribution to the state of the art with regard to arc-heater performance. The predicted envelopes provide a superior procedure for comparing supersonic arc-jet facilities. It is, therefore, suggested that future tabulations of arc heaters provide pressure and enthalpy limits plus the maximum and minimum power densities and shock pressure recovery ratio for each nozzle. These data, rather than the conventional information provided in past surveys of arc plasma heaters, would permit direct estimation of operating envelopes.

The range of heating rates and enthalpies covered by the various facilities was found to be rather broad. The facilities all had regions of overlap, so comparisons at similar operating conditions can be made during the test program.

end

III ESTIMATION OF OPERATING ENVELOPES

The original basis for consideration of potential participating organizations was Vought Astronautic's Report No. 00.49 of 18 April, 1962 (A Survey of Plasma Arc Heaters). The criteria used for the Stanford Research Institute selection were: a supersonic test capability, ability to achieve an enthalpy of 5000 Btu per lb, and a nozzle exit diameter of at least 1.5 inches. In order to obtain a large cross-section of facility designs, a lower enthalpy capability was allowed for some facilities. However, the reported information did not provide an operating envelope; it covered only ranges of enthalpy and heating rate, with no indication as to related values.

Arrangements were therefore made for a visit to each of the organizations expressing interest in the program, so that the specific capabilities of each facility could be determined. The test conditions had already been supplied, and procedures to achieve these were discussed.* Operating envelopes, if available, were therefore requested. In addition, typical performance points were obtained at each facility and tabulated on a facility evaluation form;* a summary of this information is contained in Table I.

A. Enthalpy-Pressure Envelope

Recently, Winovich[+] has derived scaling laws for arc heaters by combining the sonic flow and thermodynamic efficiency relations. These relations are used here to determine the operating envelope limits at the maximum and minimum power levels. These limits, coupled with the maximum and minimum pressure limits for the arc heater and the upper and lower enthalpy levels attainable at the facility, close the boundaries of the envelope. In the absence of specific information on enthalpy limits, a maximum level of about 15,000 Btu per lb can be assigned. Over the pressure range in which normal facilities are capable of operating, this limit corresponds to a reasonable value for the arc plasma temperature of 7000 $^{\circ}$K. The lower limit of 1500 Btu per lb for this program is arbitrarily chosen on the basis that below this value the hot wall correction of the heating rate causes too large an uncertainty in interpretation of ablation results. Therefore, this lower limit represents a practical level for obtaining meaningful evaluation data.

* Nevin K. Hiester, "Feasibility of Simulating Thermal Environments for Meaningful Evaluation of Ablating Materials". Stanford Research Institute, Quarterly Progress Report No. I, September, 1963.

\+ Winovich, W., NASA TN D 2132, "On the Equilibrium Sonic-Flow Method for Evaluating Electric-Arc Air-Heater Performance," March 1964

Table I

DATA FROM FACILITY EVALUATION FORM

Facility	Plasma Head	D_{exit} (in.)	D^* (in.)	Performance Point				Power and Pressure Limits			
				h_t (Btu/lb)	EI (kw)	P_{t_1} (atm)	W (lb/sec)	$(EI)_{max}$ (kw)	$(EI)_{min}$ (kw)	$(P_{t_1})_{max}$ (atm)	$(P_{t_1})_{min}$ (atm)
Ames, NASA	NASA Rotating Arc	2. 67	0. 75	5, 000	740	1	0. 035	900	150	2. 5	0. 10
Langley, NASA	NASA Rotating Arc	6. 6	0. 538	3, 000	2, 000	8. 8	0. 13	2, 000	1, 000	40. 0	6. 0
FMD, WPAFB	Linde Arc	7. 07	0. 375	2, 950	3, 800	52	0. 45	5, 000	800	68. 0	2. 0
Plasmadyne	Plasmadyne	3. 0	1. 0	5, 000	--	0. 48	--	1, 000	35	0. 715	0. 095
AVCO	AVCO	3. 0	1. 0	(a) 5, 200 (b) 7, 800	45. 6 59. 5	0. 591 0. 0576	0. 003 0. 003	170	15	0. 092	0. 013
General Dynamics	Vidya Rotating Arc	4. 0	0. 2	3, 377	1, 440	21. 1	0. 0486	1, 800	420	34. 0	2. 72
Goodyear	Vidya Rotating Arc	3. 0	1. 0	5, 100	522	0. 70	0. 0165	1, 000	150	1. 0	0. 039
Martin-Marietta	Modified Plasmadyne	1. 5	0. 5	10, 500	96	0. 0868	0. 001	150	10	0. 10	0. 005
Boeing	Boeing Rotating Arc	3. 0	0. 72	(a) 2, 100 (b) 5, 221	41 59	0. 298 0. 171	0. 0197 0. 0085	178	30	0. 50	0. 10
North American	Modified Thermodynamics	2. 5 3. 5	0. 70 1. 0	4, 060	354	0. 733	0. 049	650	63	5. 5	0. 35
General Electric	Tandem Gerdien	1. 192	0. 156	13, 600	230	1. 3	0. 0015	300	75	1. 6	1. 0

From sonic flow of air for the enthalpy range between 1100 and 15,000 Btu per lb, the superficial mass velocity and pressure are related to the total enthalpy by

$$W/A^{*} p_{t_1} = 280 h_t^{0.4} \quad \text{(Eq. 1)}$$

where W = mass flow rate of air through the throat, pounds per second

A^{*} = throat area, square feet

p_{t_1} = arc chamber pressure, atmospheres

h_t = average enthalpy of plasma stream at the nozzle throat, Btu per pound.

A small pressure effect exists for Eq. 1; however, it is negligible for the present consideration. From the definition of thermodynamic, or energy conversion, efficiency

$$\eta = W (h_t - h_o)/EIJ \quad \text{(Eq. 2)}$$

where η = thermodynamic efficiency

h_o = enthalpy of air entering the arc, Btu per pound

EI = power input to the arc electrodes, kilowatts

J = conversion factor (0.947 Btu per kilowatt-second).

Combining Eqs. 1 and 2, and neglecting h_o (valid for air entering at enthalpies below 1000 Btu per lb), the plasma enthalpy is given by

$$h_t = (\eta\, EIJ/280A^{*})^{1.67} (p_{t_1})^{-1.67}. \quad \text{(Eq. 3)}$$

The first term is the power transferred to the air plasma per unit throat area (the power density) and the second term indicates the effect of arc chamber pressure on enthalpy at constant power density.

Equation 3 will normally be used with a constant thermodynamic efficiency obtained from the performance point deduced by Eq. 2 from the data supplied in the facility evaluation form. Generally, the efficiency will vary with the operating pressure and enthalpy level. Consequently, the shape of the operating envelope may be altered from that predicted by the scaling law formulation used here. However, on the assumption that the variation of efficiency will be similar for all facilities operating over the same limits and with somewhat similar arc-heaters, valid comparisons can be made between these estimated envelopes.

B. Stagnation-Point Heating Envelope

Once the enthalpy-arc chamber pressure envelope has been calculated, one can estimate the enthalpy-heating rate envelope by employing the normal shock pressure recovery ratio and the Fay-Riddell[+] heating-rate relation. The formulation employed is for laminar flow at the stagnation point of a hemisphere; however, it can be applied to blunt axisymmetric bodies as well.

The pressure recovery ratio, p_{t_2}/p_{t_1}, is a weak function of enthalpy level and is determined almost entirely by the area ratio of the nozzle; that is, the ratio of the exit area to the throat area.[++] This information permits determination of the stagnation pressure, p_{t_2}, from the arc chamber pressure, p_{t_1}.

The heating rate formula, derived from the Fay-Riddell analysis with a Lewis number of 1.0 and a Prandtl number of 0.72, is

$$\dot{q} = 0.0417\sqrt{\frac{p_{t_2}}{R}}\,(h_t - h_w) \qquad \text{(Eq. 4)}$$

where $\dot{q}$ = heating rate, Btu per sec per square foot

p_{t_2} = stagnation pressure, atmospheres

R = effective radius of curvature for test model, feet

h_w = wall enthalpy, Btu per pound.

Combining this with the shock pressure recovery ratio gives the relation between stagnation point heat transfer rate, arc chamber pressure, and enthalpy

$$\dot{q} = 0.0417\sqrt{\frac{p_{t_1}}{R}\left(\frac{p_{t_2}}{p_{t_1}}\right)}\,(h_t - h_w). \qquad \text{(Eq. 5)}$$

[+] Fay, J., F. Riddell, "Theory of Stagnation Point Heat Transfer in Dissociated Air," J. Aeronautical Sci., V. 25, pp. 73-85, 121, Feb. 1958

[++] Yoskikawa, K., E. Katzen, "Charts for Air-Flow Properties in Equilibrium and Frozen Flows in Hypervelocity Nozzles," NASA TN D693, April 1961

In the current program R has been taken to be four times the actual radius of the flat-faced blunt body. This figure is suggested on the basis of theoretical considerations of shock wave studies between hemispheres and blunt bodies which provide their relative velocity gradients.[+] The correction term for the hemisphere heating rate formula is equivalent to specifying an equivalent hemispherical radius of curvature that is four times that of the actual cylindrical radius of the flat-faced blunt body.
Thus,

$$R = \frac{(4)\,(1.25)}{(2)\,(12)} = 0.208 \text{ ft},$$

since the diameter of the test specimen is 1.25 inches.

C. Numerical Example of Envelope Calculations

The following example indicates the use of these relations to estimate performance limits for operating envelopes. The data supplied by General Dynamics, Fort Worth, and given in Table I, are used because they best exemplify the three types of operating envelope limits mentioned earlier.

The energy conversion efficiency is found by Eq. 2 to be

$$\eta = \frac{(0.0486)\,(3377)}{(1440)\,(0.95)} = 0.12.$$

The throat area

$$A^* = \frac{\pi}{4}\left(\frac{0.2}{12}\right)^2 = 2.18 \times 10^{-4} \text{ sq ft.}$$

Using this η and the first term on the right-hand side of Eq. 3, the maximum power density is

$$\frac{\eta EIJ}{280A^*} = \frac{(0.12)(1800)(0.947)}{(280)(2.18 \times 10^{-4})} = 3360 \text{ Btu per sec ft}^2.$$

And the minimum is

$$\frac{(0.12)(420)(0.947)}{(280)(2.18 \times 10^{-4})} = 785 \text{ Btu per sec ft}^2.$$

+ Kaattari, George E. "Predicted Shock Envelopes About Two Types of Vehicles at Large Angles of Attack," NASA TN D860, April 1961

At the maximum power density the enthalpy at an arc chamber pressure of ten atmospheres is given by Eq. 3 as

$$h_t = (3360)^{1.67} (10)^{-1.67} = 16,100 \text{ Btu per lb}$$

and at a p_{t_1} of 30 atmospheres

$$h_t = (3360)^{1.67} (30)^{-1.67} = 2520 \text{ Btu per lb}$$

and the minimum power density

$$h_t = (785)^{1.67} (3)^{-1.67} = 10,400 \text{ Btu per lb}$$
$$\text{at } p_{t_1} = 3 \text{ atmospheres}$$

$$h_t = (785)^{1.67} (10)^{-1.67} = 1434 \text{ Btu per lb}$$
$$\text{at } p_{t_1} = 10 \text{ atmospheres.}$$

These points are used to draw the power density limits to the envelope as shown by the light dashed lines on the right-hand side of Fig. 1. The pressure limits from Table I and the upper and lower enthalpy limits mentioned earlier are also shown and the operating envelope is considered to be the minimum enclosed envelope between the power density limits. This area is indicated by the light solid line along the dashed limits.

The heating rate envelope can now be determined. First the area ratio is calculated as

$$A/A^* = \left(\frac{D_{exit}}{D^*}\right)^2 = \left(\frac{4}{0.2}\right)^2 = 400.$$

From TN D693 the pressure recovery ratio for this value of A/A^* is

$$p_{t_2}/p_{t_1} = 0.005.$$

Thus, from Eq. 5, for the nozzle considered, and neglecting h_w, which is a minor correction within the enthalpy limits chosen,

$$\dot{q} \cong 0.0417 \sqrt{\frac{0.005\, p_{t_1}}{0.208}}\, (h)_t = 0.0065 \sqrt{p_{t_1}}\, (h_t). \qquad \text{(Eq. 6)}$$

This final relation, which applies to the specific facility considered, is then used with the values of h_t and p_{t1} at each of the six corners of the enthalpy arc chamber pressure envelope to determine the heating rate

enthalpy envelope. For instance, at the upper right-hand corner of the envelope on the right-hand side

$$h_t = 15,000 \text{ Btu per lb and } p_{t_1} = 10.5 \text{ atmospheres.}$$

Then, from Eq. 6,

$$\dot{q} = (0.0065)\sqrt{10.5}\ (15,000) = 317 \text{ Btu per ft}^2 \text{ per sec.}$$

These data are plotted on the left-hand side of Fig. 1.

The value of heating rate, $\dot{q}$, given by this figure, and the remaining figures, can be converted to $\dot{q}\sqrt{R}$ by multiplying by $\sqrt{0.208}$ ft. Thus, in terms of $(\text{Btu})(\text{ft})^{1/2}$ per $(\text{ft})^2$ (sec), $\dot{q}\sqrt{R} = 0.456\ \dot{q}$.

As a matter of interest, General Dynamics supplied preliminary information describing their heating rate-enthalpy envelope+ and it is indicated as a heavy solid line on the right-hand side. It is interesting to note that the two envelopes are relatively similar.

+ Report AT-7 "The General Dynamics/Fort Worth, Arc-Heated Hyperthermal Research Facility," 1 October, 1962, Fig. 12

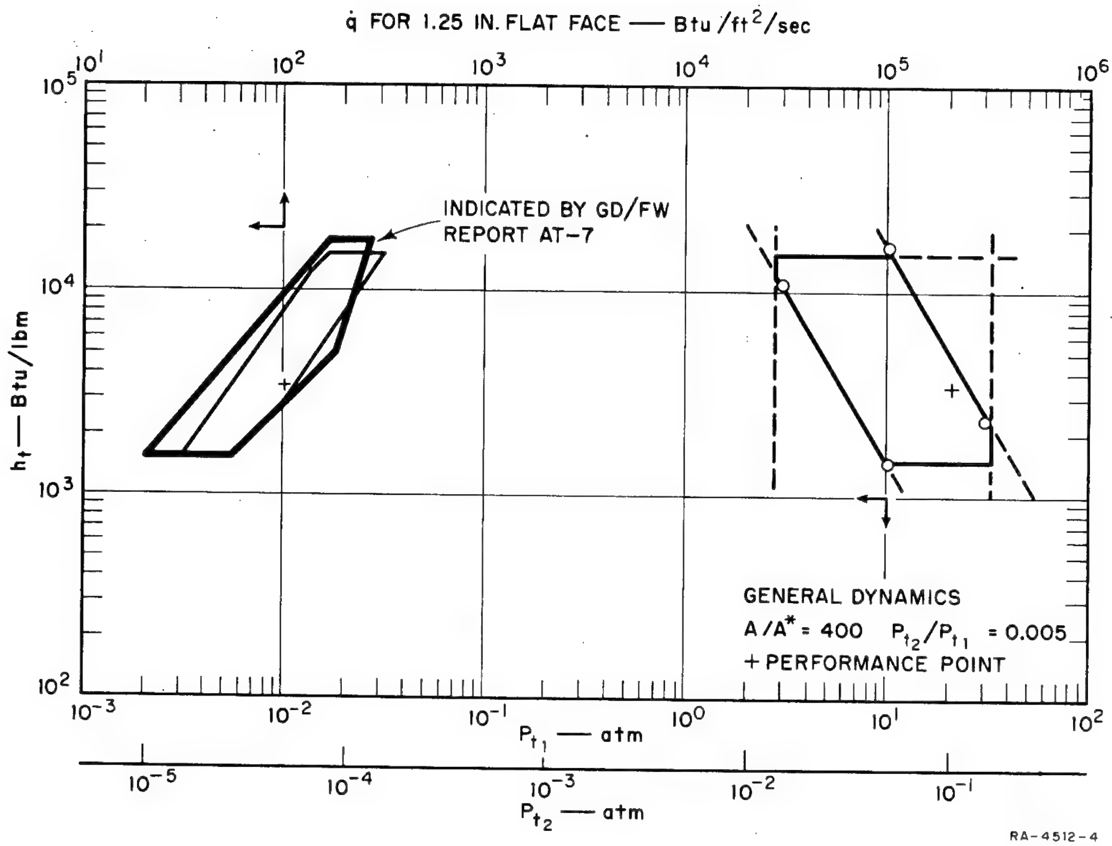

FIG. 1 ESTIMATION OF OPERATING ENVELOPES

IV COMPARISON OF ESTIMATED AND INDICATED ENVELOPES

The techniques described above and the data contained in Table I were used to estimate operating envelopes for the other participating organizations. These are presented in Figs. 2-11 as the envelopes bounded by the connected light dotted and dashed lines.

A copy of the pertinent figure was sent to each organization with an explanation of how it had been estimated. Each facility was then asked to provide any later heat rate-enthalpy data, along with dimensions of the calorimeter on which the heat rate data were determined. The information supplied, after being corrected for the appropriate R value (using Eq. 4), has been plotted in each figure as the heavy solid lines. In some cases, enthalpy-arc chamber pressure information was also given, and these envelopes have also been indicated by the heavy solid lines on the right-hand side of the appropriate figures.

It will be noted that in many cases the upper and lower enthalpy limits indicated by the organization are quite different from the 15,000 and 1500 Btu per lb values assumed earlier. The estimated envelopes have been corrected for this by changing the maximum and minimum enthalpy limits to the values shown by each organization, and the connected light dashed and solid lines give the new predicted envelopes. It is these latter envelopes that should be compared with those indicated by the organization. It also should be realized that some of the indicated envelopes are based on limited actual data and may in themselves be predictions by the organization concerned.

Finally, the predicted envelopes are based on ideal test conditions; improper placement of the model, nonuniformity of the plasma stream with respect to pressure and enthalpy distribution, plasma contamination, and catalytic action of the calorimeter surface, can all effect the measured heating rates considerably.

A review of the estimated and indicated envelopes is of interest. The two heating rate envelopes compare very well for the Ames Research Center (Fig. 2).

In Fig. 3, for Langley Research Center, the actual minimum pressure limit is less than that originally reported, and it would also appear that maximum and minimum power inputs reported cover a much narrower range than actually experienced. Even so, there is a reasonably good comparison between the predicted and indicated envelopes.

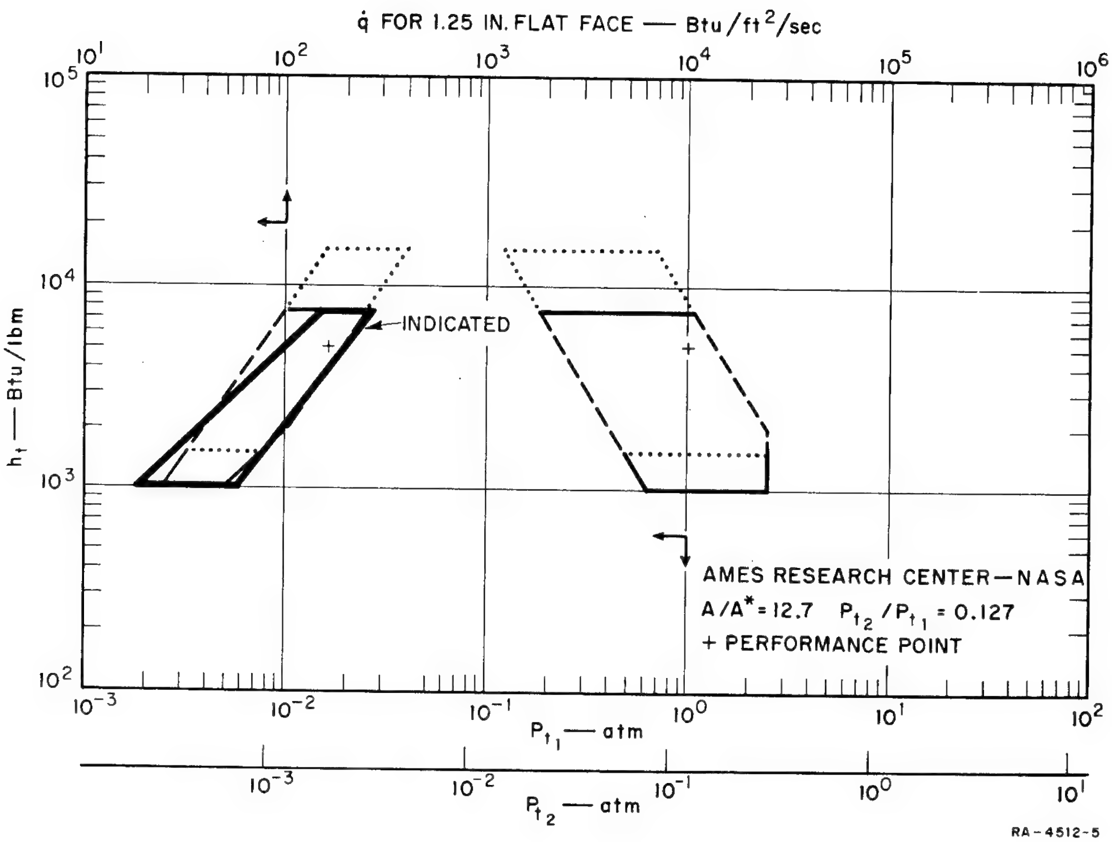

FIG. 2 ESTIMATED AND INDICATED ENVELOPES FOR AMES RESEARCH CENTER, NASA

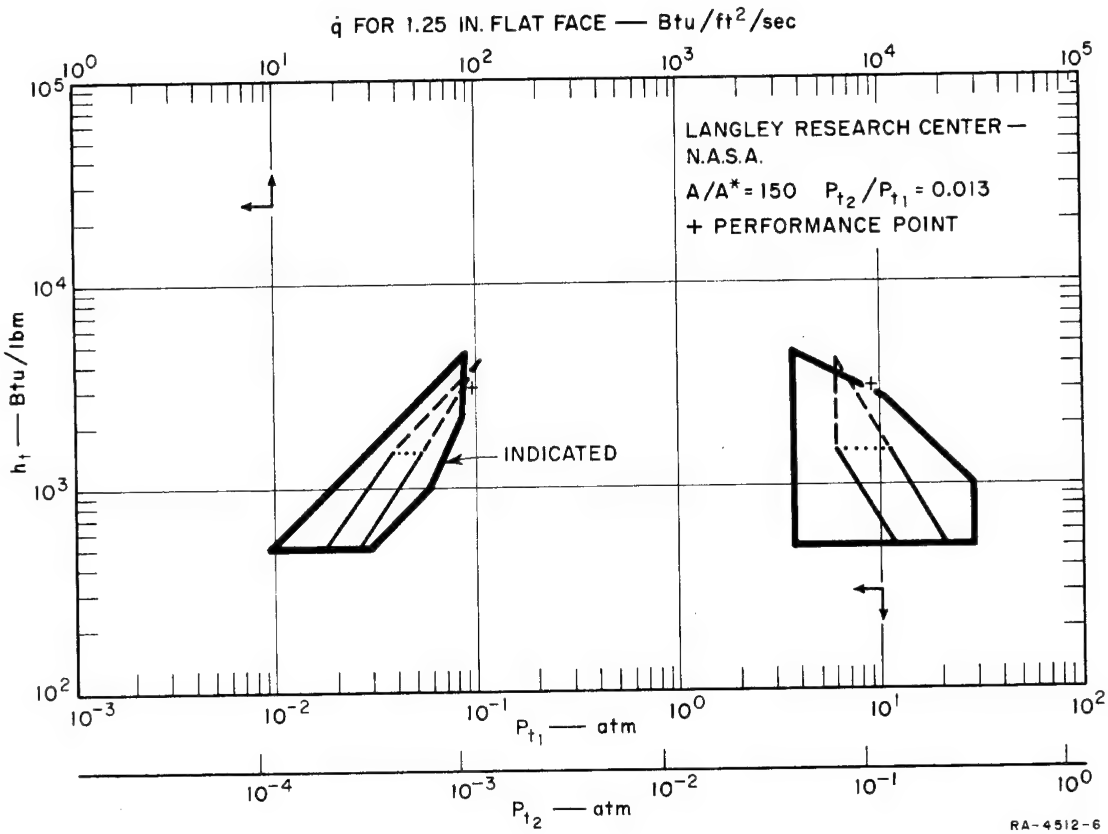

FIG. 3 ESTIMATED AND INDICATED ENVELOPES FOR LANGLEY RESEARCH CENTER, NASA

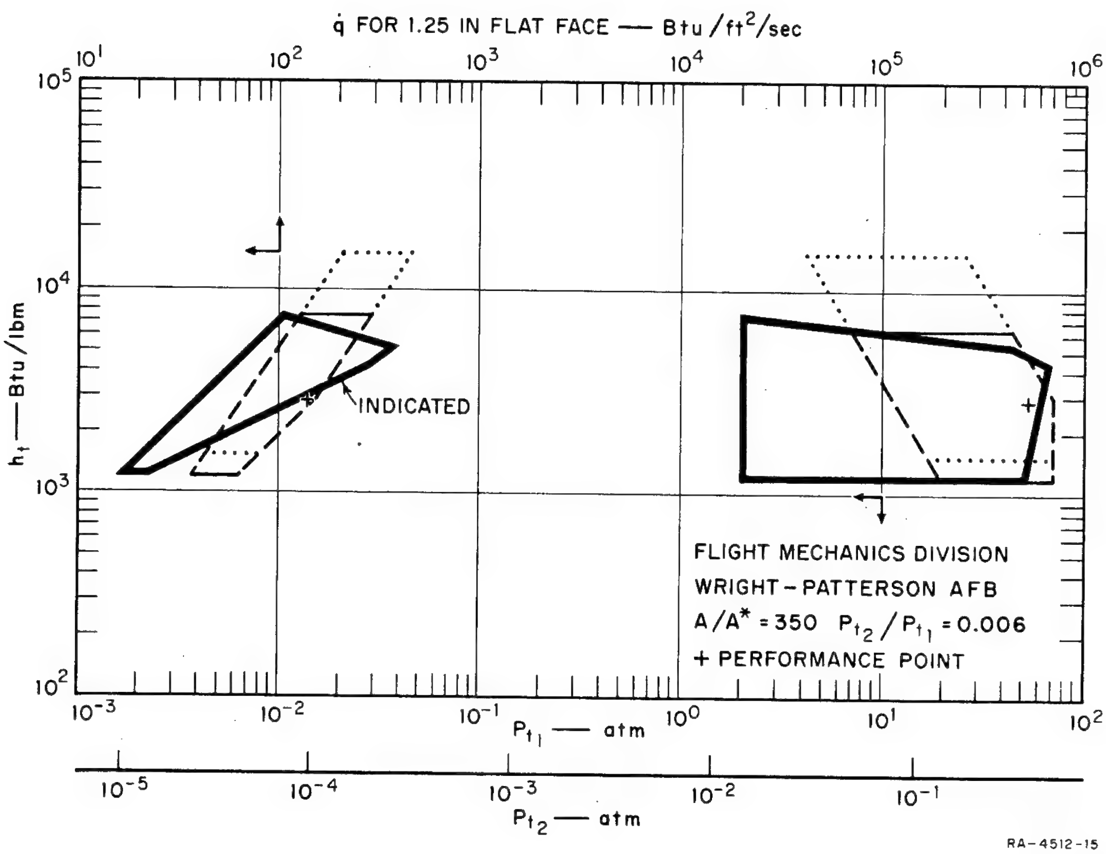

FIG. 4 ESTIMATED AND INDICATED ENVELOPES FOR FLIGHT MECHANICS DIVISION, WRIGHT-PATTERSON AIR FORCE BASE

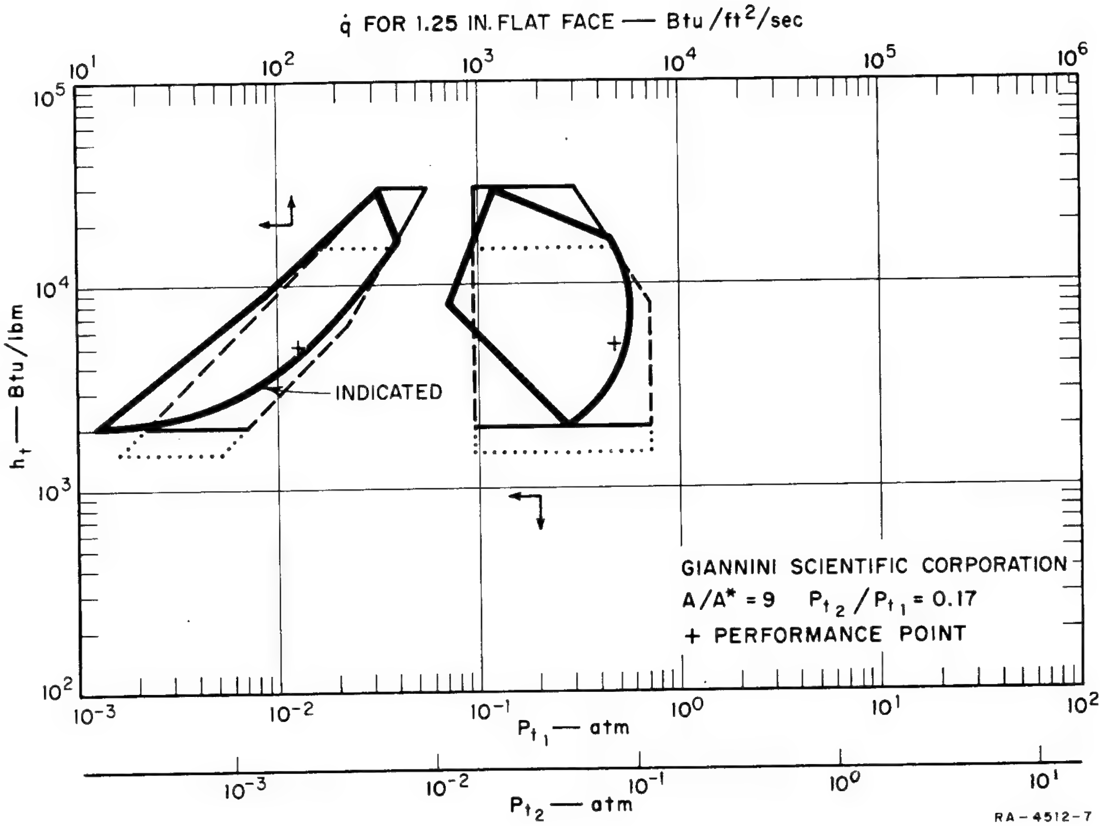

FIG. 5 ESTIMATED AND INDICATED ENVELOPES FOR GIANINNI SCIENTIFIC CORPORATION

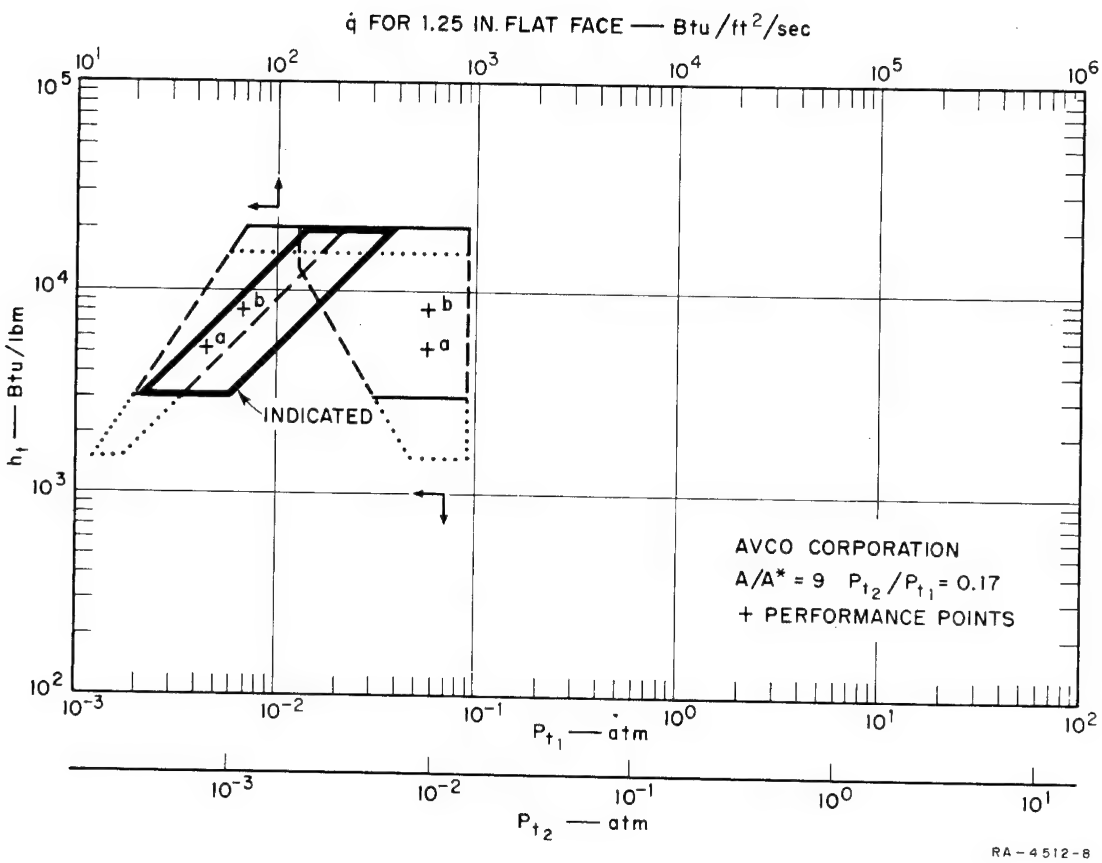

FIG. 6 ESTIMATED AND INDICATED ENVELOPES FOR AVCO CORPORATION

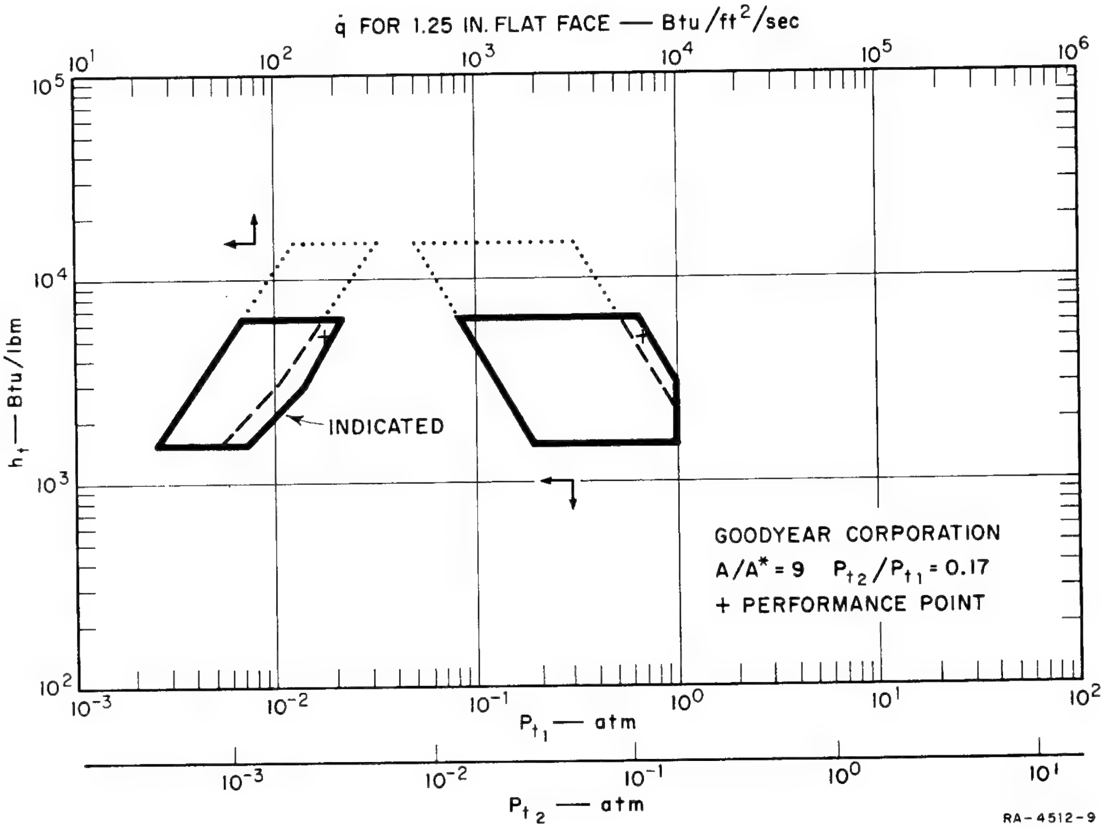

FIG. 7 ESTIMATED AND INDICATED ENVELOPES FOR GOODYEAR CORPORATION

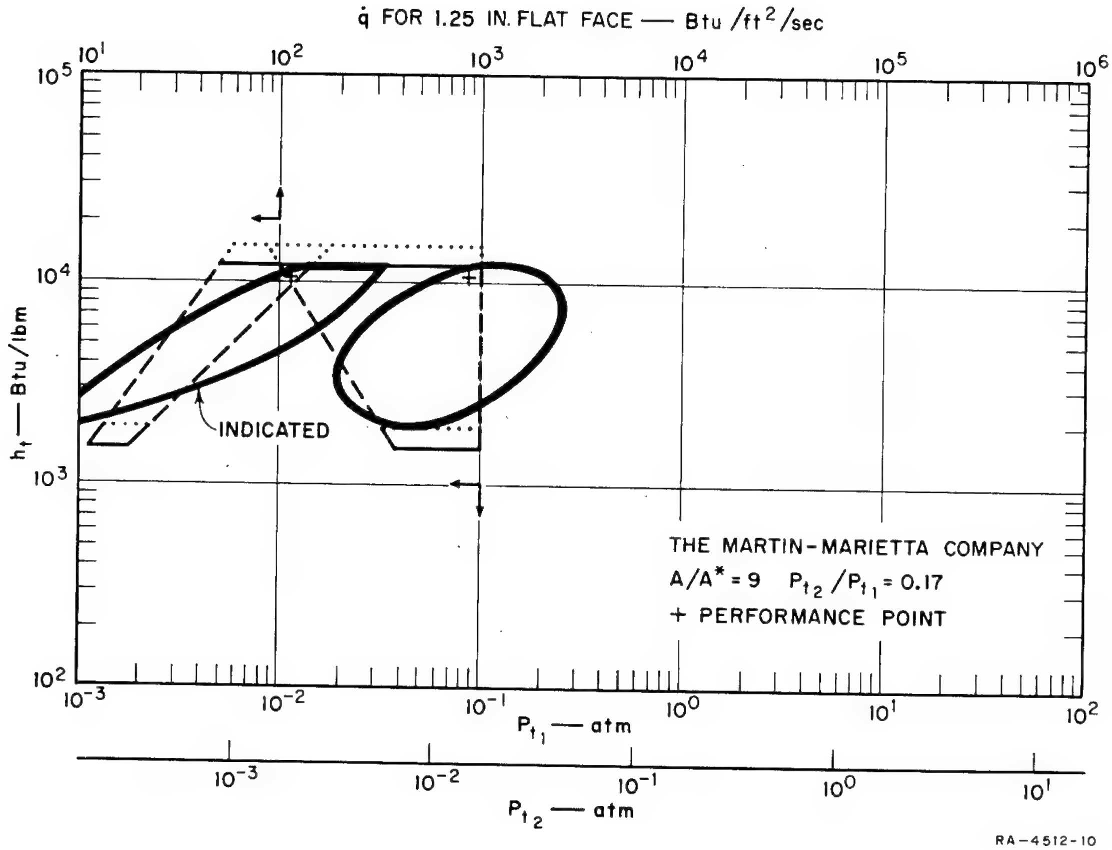

FIG. 8 ESTIMATED AND INDICATED ENVELOPES FOR MARTIN-MARIETTA COMPANY

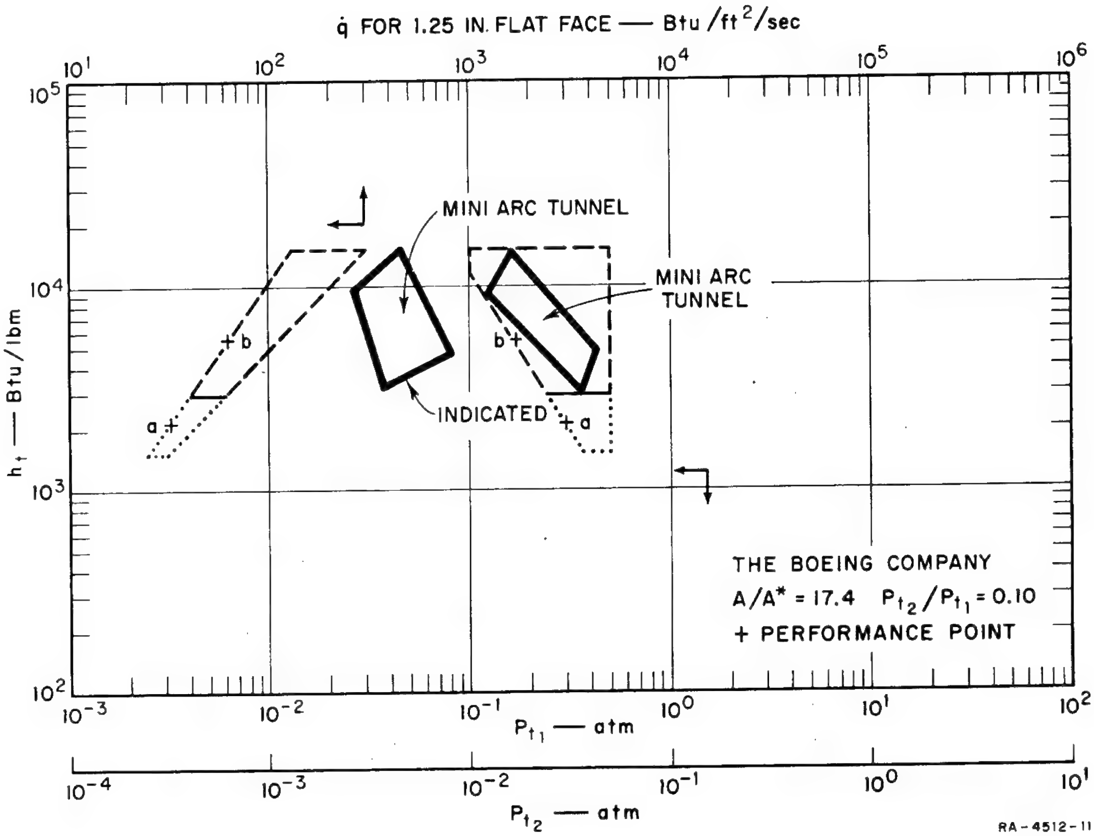

FIG. 9 ESTIMATED AND INDICATED ENVELOPES FOR THE BOEING COMPANY

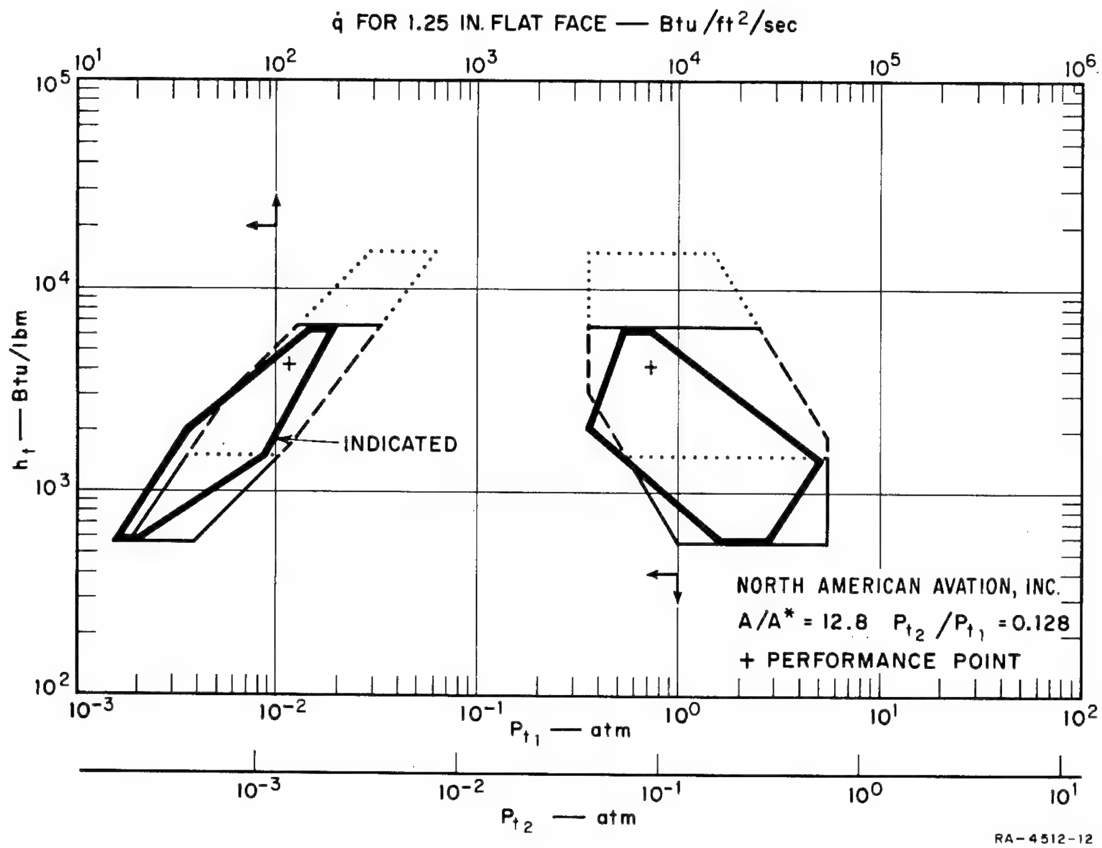

FIG. 10 ESTIMATED AND INDICATED ENVELOPES FOR NORTH AMERICAN AVIATION

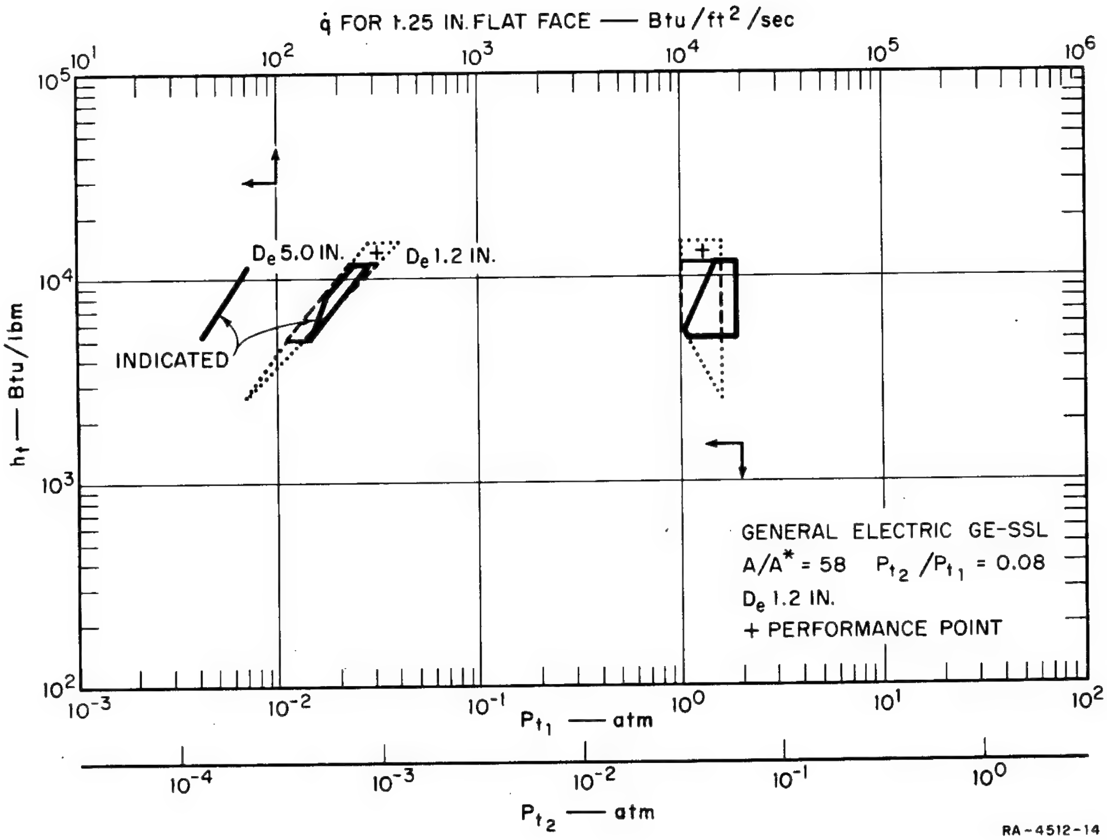

FIG. 11 ESTIMATED AND INDICATED ENVELOPES FOR GENERAL ELECTRIC

The information from the Flight Mechanics Division, Wright-Patterson Air Force Base (Fig. 4) shows a considerably smaller minimum pressure than originally reported. Otherwise there is fair correspondence between the predicted and indicated envelopes.

In Fig. 5, covering Giannini Scientific (Plasmadyne), there is again a quite good correspondence between the estimated and indicated values. There appears, however, to be a lower power input limit not reported, and the efficiency apparently falls off at lower enthalpies.

The AVCO data (Fig. 6) show some difference between the predicted and indicated values. The major item to be noticed is that the maximum pressure limit appears to be greater than indicated.

The estimated-indicated envelopesfor Goodyear (Fig. 7) match very well; the only difference appears to be a slightly higher maximum power input than indicated.

The results from Martin-Marietta (Fig. 8) are quite difficult to explain. First, the indicated heat rate-enthalpy and enthalpy-arc chamber pressure envelopes are not consistent with each other according to heating rate formula derived from the Fay-Riddell analysis. However, if we take the two envelopes separately, the latter one indicates a higher maximum pressure limit than previously reported. The heat rate-enthalpy envelope can only be explained by assuming that the thermodynamic efficiency decreases with increasing arc chamber pressure.

Somewhat similar comments can be made about Boeing (Fig. 9). The two operating envelopes for the Mini-Arc Tunnel are not consistent with the Fay-Riddell relation, although the indicated enthalpy-arc chamber pressure envelope matches the estimated one reasonably well. This latter envelope would appear to indicate a lower maximum power input level than had been reported. The divergence between the estimated and indicated values for the heat rate-enthalpy envelope is possibly due to location of the calorimeter at the initial shock front node in the stream, causing increases in stagnation pressure and/or velocity gradient to affect the heating rate.

North American (Fig. 10) again shows quite good correspondence between estimated and indicated envelopes. The major comment that can be made is that it would appear that the maximum power input level may be less than that reported and that the energy conversion efficiency seems to increase with arc chamber pressure, or conversely that the efficiency decreases with increasing enthalpy.

In Fig. 11, the indicated and estimated envelopes for the General Electric facility match quite well.

The indicated heat rate-enthalpy envelopes for each organization except for Boeing have been superimposed, and the heavy solid line in Fig. 12 outlines the limits of this composite. Several of the individual envelopes are indicated to show how they fit these limits. There is no single common operating region for all of these facilities, although the envelope for each overlaps at least one other. In addition, the total area covered by the combined operating envelopes is relatively broad. It is, therefore, apparent that in the present round-robin ablation program experimental points at each facility can be tied to every other facility either directly or through a facility whose envelope overlaps portions of both.

It is of interest to consider the testing ranges provided by these eleven facilities. Ten can achieve enthalpies of 5000 Btu per lb and five can achieve 10,000. Also, ten can achieve heating rates of 100 Btu per ft^2 per sec at enthalpies of 5000 Btu per lb, and five can achieve 150 with the Stanford Research Institute blunt calorimeter, i. e., for an effective radius of curvature of 0.208 ft.

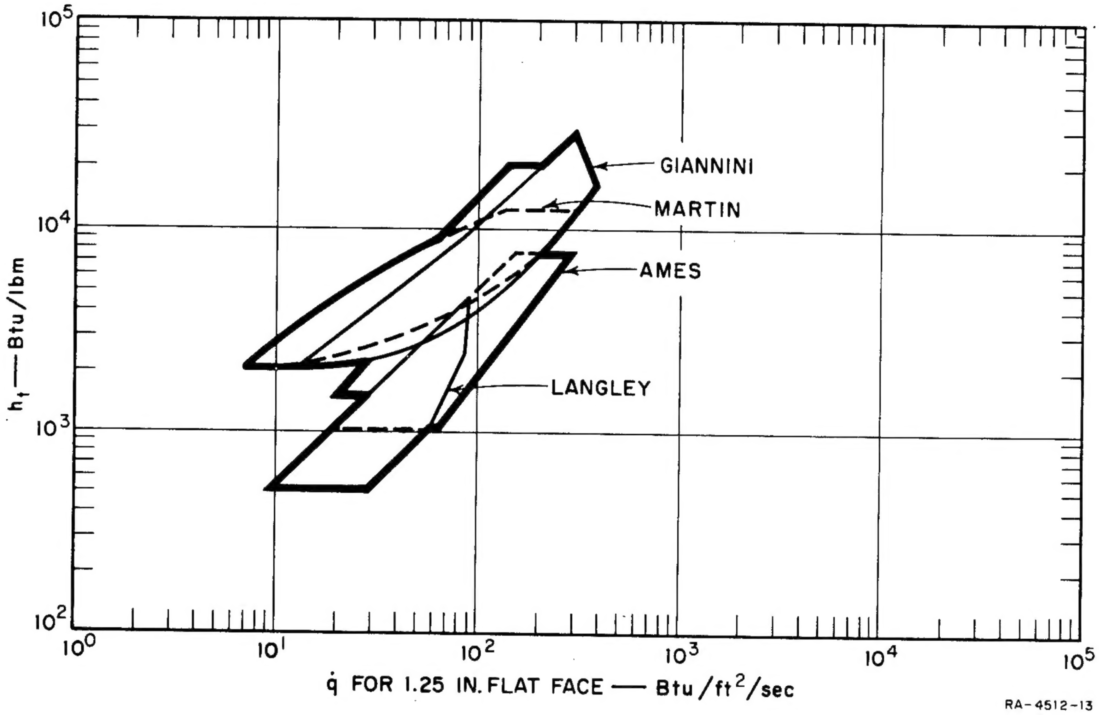

FIG. 12 OVER-ALL CAPABILITIES OF COOPERATING FACILITIES

NASA-Langley, 1964 CR-99

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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